

# Parallel interaction-free measurement using spatial adiabatic passage.

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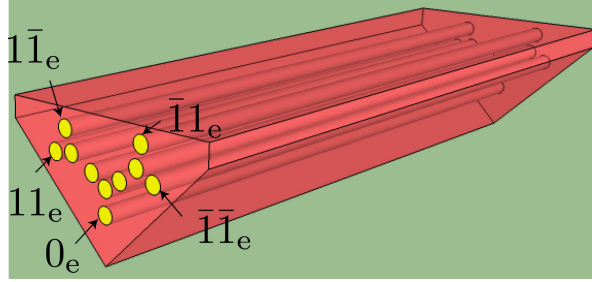
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**Abstract.** Interaction-free measurement is a surprising consequence of quantum interference, where the presence of objects can be sensed without any disturbance of the object being measured. Here we show an extension of interaction-free measurement using techniques from spatial adiabatic passage, specifically multiple receiver adiabatic passage. Due to subtle properties of the adiabatic passage, it is possible to image an object without interaction between the imaging photons and the sample. The technique can be used on multiple objects in parallel, and is entirely deterministic in the adiabatic limit. Unlike more conventional interaction-free measurement schemes, this adiabatic process is driven by the symmetry of the system, and not by more usual interference effects. As such it provides an interesting alternative quantum protocol which may be applicable to photonic implementations of spatial adiabatic passage. We also show that this scheme can be used to implement a collision-free quantum routing protocol.

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**Figure 1.** Multi-waveguide concept diagram for a four-leaf MRAP device, such as can be realised using direct-write technology. Waveguides are represented as circular tubes through the device. In this device, the adiabatic protocol coherently sends photons from the input node,  $|0_e\rangle$  to an equally weighted superposition  $(1/2)(|11_e\rangle + |\bar{1}1_e\rangle + |\bar{1}\bar{1}_e\rangle + |\bar{1}\bar{1}_e\rangle)$ , as indicated.

## 1. Introduction

One of the counter-intuitive effects of quantum mechanics is that of interaction-free measurement (IFM). Classically, one can only obtain information about the location of an object by interacting particles with it. For example, by absorption or deflection of the particles. In every case there is an inevitable interaction between the sensing particles, and the object being sensed. However, Dicke [1], and later Elitzur and Vaidman [2] showed that it is possible to perform an IFM, i.e. a measurement where the sensing particles have never interacted with the object, and yet provide definitive information about its existence. To illustrate IFMs we summarise the canonical IFM: the ‘quantum bomb’ problem.

Assume that we are searching for a bomb. However this bomb is so sensitive that if a single photon touches it, it will explode: an undesirable outcome. How can we design an optical sensing system that detects the presence or absence of the bomb without setting it off? Elitzur and Vaidman showed that this task can be achieved non-deterministically. They considered a Mach-Zehnder interferometer, balanced so that when both arms are unobstructed, photons always exit via the bright port. However if a bomb is placed in one of the arms, then there is a 50% chance of detecting the photon at the dark port, and hence detection at the dark port proves the presence of a bomb without the photon having interacted with the bomb.

The quantum bomb protocol is non-deterministic: the bomb is triggered 50% of the time, and detection of a photon at the bright port does not provide information about the presence or absence of the bomb. Nonetheless this is an important protocol which performs a task not possible classically. The success probability of this protocol can be asymptotically increased to unity [3]. It is also possible to perform multiple imaging and this was used to demonstrate high-resolution images [4]. Variants of IFM lead to the possibility of counter-factual quantum computation, where the result of a quantum algorithm is determined without the qubits actually performing the algorithm [5].

All of the above protocols have at their heart interferometry. As such they are sensitive to issues such as alignment and/or timing. We are considering an alternative approach to IFM based on adiabatic passage. As such, instead of relying on interferometry to perform the measurement, we use the symmetry of the problem, in particular the composition of the null space of the solution to the adiabatic network,

as will be described below. This gives a fundamentally different approach to the task of IFM, which gives rise quite naturally to parallel search with robustness and deterministic sensing. Returning to the quantum bomb analogy, we can think of our scheme as allowing the imaging of a quantum minefield, with multiple quantum bombs distributed at unknown spatial locations. The adiabatic network can best be achieved using an integrated multi-waveguide approach, leveraging the advances direct-write lithography [6] for quantum photonics [7], and as such can be seen as an extension of the demonstrations of waveguide Coherent Tunneling Adiabatic Passage (CTAP) by Longhi and co-workers [8, 9, 10]. A concept diagram of our envisaged device is shown in Fig. 1.

Techniques for adiabatic passage are used to evolve quantum states so that the system remains in an instantaneous eigenstate, but the Hamiltonian is varied as a function of time. The requirement for adiabaticity implies that the Hamiltonian must be changed sufficiently slowly so that population is unable to leak between the eigenstates. Such techniques are well known, especially in atomic and molecular systems [11]. Advances in the construction of quantum systems have allowed new perspectives in adiabatic passage, in particular the opportunity to move particles adiabatically through space. To explain this we first discuss CTAP as a precursor adiabatic passage protocol, before showing how this can be extended to multiple recipients.

CTAP is an all-spatial variant of the well-known STIRAP (STImulated Raman Adiabatic Passage) technique [12]. The simplest form of CTAP requires a single particle which can be placed in a coherent superposition of three spatially-defined quantum states. Canonical CTAP effects particle motion between the two outermost sites by adiabatic variation of the tunnel matrix elements between neighbouring sites. It uses the counter-intuitive pulse sequence, where the tunnel matrix element between the sites where the particle is *not* present is initially high, whereas the tunnel matrix element connected to the site with the particle is initially zero. The counter-intuitive pulse sequence affords considerable robustness to the transport protocol and has the surprising property that the particle is never found at the central site. CTAP has been studied theoretically for electrons [13], atoms [14, 15], BECs [16, 17], and superconductors [18], and was recently demonstrated with photons [9].

Techniques based on spatial adiabatic passage have a considerable advantage over their more familiar quantum optical counter-parts. With atomic and molecular systems, the Hilbert space of the system is defined by the physics of the system under investigation. By contrast, advances in nano-fabrication give the intriguing ability to *engineer* a desired Hilbert space by technologies such as lithography or the application of spatially varying optical fields. This ultimately provides new flexibility and the potential to realise novel quantum devices. CTAP can be extended using linear schemes that extend the number of sites over which transport can occur. The quantum optical versions of these extensions are the alternating [19] and straddling [20] STIRAP schemes, and these have been investigated in the context of CTAP. The straddling CTAP scheme was first considered in Ref. [13] and later demonstrated with photons [10], and the alternating scheme has also been investigated [21, 22]. The alternating scheme is particularly interesting for interferometric schemes and non-trivial loop topologies because of the transient population, which allows for sensing, and in this context a scheme for an adiabatic electrostatic Aharonov-Bohm interferometer has been proposed [23].

This paper is organised as follows. We first discuss the extension of the Multiple

Recipient Adiabatic Passage (MRAP) protocol to account for large scale quantum networks, and discuss some of the properties of the null space of the resulting Hamiltonian. We then show an application of this protocol to the task of parallel IFM in the quantum minefield problem. Following this, we explore some practical limitations in terms of ensuring the adiabaticity of the protocol. Finally we show how this protocol can be converted into collision-free quantum routing technique.

## 2. Multiple Recipient Adiabatic Passage and quantum tree networks

The possibility of engineering Hilbert spaces by spatial location of quantum sites, provides many opportunities for the realisation of novel devices. Here we focus on the ability to engineer branched quantum networks. One proposal for a branched adiabatic passage scheme is Multiple Reciever Adiabatic Passage, MRAP [24]. This was investigated as a form of quantum fanout, useful for the direct synthesis of operator measurements [25].

The dynamics of the MRAP tree are governed by the system Hamiltonian, depicted schematically in Figure 2. We assume that the energy of the particle at any site is the same, and hence the Hamiltonian is solely defined by the adjacency matrix. To label the tree, first note that each node other than the zeroth node, either has two connections or three connections, corresponding to whether there is an odd number of links to the initial node, or an even number respectively. We choose to label those sites with an odd number of links with  $o$ , and those with an even number  $e$ . We next number all of the  $e$  sites by the path taken to reach them using a balanced ternary notation according to Figure 2, where up pathways are denoted by adding the digit 1 to the right hand side (least significant digit) of the number, and down pathways by the digit  $\bar{1}$ . The  $o$  sites are numerically labelled with the same number as the site to their immediate left.

The tunnel matrix element (TME) connecting states follows the alternating convention, which also be considered as an  $A - B$  chain. The strength of a connection between states in the order  $e - o$  is  $A$ , and between  $o - e$  is  $B$ , as shown in Figure 2. The magnitudes of all of the  $A$  TMEs are the same, as are all the  $B$ . The values of the couplings are varied according to the counter-intuitive pulse sequence (also employed in CTAP). This pulse sequence initially has coupling  $B$  on, rather than the intuitive way of operating which would raise  $A$  first. For simplicity we choose a sinusoidal variation of TME with time,  $t$ , i.e.

$$A(t) = \sin^2(\pi t/2T), \quad B(t) = \cos^2(\pi t/2T), \quad (1)$$

where  $T$  is the total time of the protocol and the maximum values of the TMEs are normalised to unity.

The general form of our MRAP Hamiltonian is

$$\begin{aligned} H = & A \sum_k \left( a_{ko}^\dagger a_{ke} \right) + B \sum_k \left( a_{3k+1o}^\dagger a_{ke} a_{3k-1o}^\dagger a_{ke} \right) \\ & + A \sum_k \left( a_{ki}^\dagger a_{ke} \right) + B \sum_k \left( a_{kj}^\dagger a_{ki} \right) + \text{h.c.}, \end{aligned} \quad (2)$$

where  $a$  ( $a^\dagger$ ) is the usual annihilation (creation) operator,  $k$  sums over all sites in the tree. The particle distribution via tree is achieved by the  $e$  and  $o$  sites, as per the first two sums in the Hamiltonian, whilst the second sums effect the CTAP like imaging plane.



$|\bar{1}1_j\rangle$ . The strength of interaction between two waveguides is labelled by ‘A’ and ‘B’.

Although we discuss the MRAP protocol in an arbitrary, decoherence-free setting, it is clear that decoherence will be deleterious to the protocol. The ideal method of realising this scheme would therefore be in an optical setting using waveguides such as those demonstrated in Refs. [9, 10]. In such schemes, each site is replaced by a waveguide, and the tunnel matrix element between sites controlled by varying the proximity of the waveguides. Varying proximity changes the evanescent tails of the

modes, and hence their overlap. In this way the *temporal* variation of the adiabatic passage is translated into a *spatial* evolution, but the essential characteristics of the evolution are unaltered between representations.

The Hamiltonian in matrix form of a two-leaf MRAP structure is

$$H_2 = \begin{bmatrix} 0 & A & 0 & 0 \\ A & 0 & B & B \\ 0 & B & 0 & 0 \\ 0 & B & 0 & 0 \end{bmatrix}, \quad (3)$$

with basis ordering  $\{|0_e\rangle, |0_o\rangle, |1_e\rangle, |\bar{1}_e\rangle\}$ . The identical on-site energies have been subtracted. The null space of this Hamiltonian is spanned by [25].

$$|D_1^{(2)}\rangle = \frac{B|0_e\rangle - A|1_e\rangle}{\sqrt{A^2 + B^2}}, \quad |D_{\bar{1}}^{(2)}\rangle = \frac{B|0_e\rangle - A|\bar{1}_e\rangle}{\sqrt{A^2 + B^2}}. \quad (4)$$

This spanning ensures that under adiabatic evolution, a particle initially in  $|0_e\rangle$  will be transported to a coherent superposition  $-(|1_e\rangle + |\bar{1}_e\rangle)/\sqrt{2}$ , without any population even transiently being present in site  $|0_o\rangle$ .

To create the Hamiltonian for the entire MRAP tree, leaf nodes are replaced by the Hamiltonian  $H_2$ , so for example, the four-leaf MRAP tree would be

$$H_4 = \begin{bmatrix} 0 & A & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ A & 0 & B & B & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & B & 0 & 0 & A & 0 & 0 & 0 & 0 & 0 \\ 0 & B & 0 & 0 & 0 & A & 0 & 0 & 0 & 0 \\ 0 & 0 & A & 0 & 0 & 0 & B & B & 0 & 0 \\ 0 & 0 & 0 & A & 0 & 0 & 0 & 0 & B & B \\ 0 & 0 & 0 & 0 & B & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & B & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & B & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & B & 0 & 0 & 0 & 0 \end{bmatrix}, \quad (5)$$

with basis ordering  $\{|0_e\rangle, |0_o\rangle, |1_e\rangle, |\bar{1}_e\rangle, |1_o\rangle, |\bar{1}_o\rangle, |11_e\rangle, |1\bar{1}_e\rangle, |\bar{1}1_e\rangle, |\bar{1}\bar{1}_e\rangle\}$ . The null space is spanned by the vectors

$$|D_{11}^{(3)}\rangle = \frac{B^2|0_e\rangle - AB|1_e\rangle + A^2|11_e\rangle}{\sqrt{A^4 + A^2B^2 + B^4}}, \quad (6)$$

$$|D_{1\bar{1}}^{(3)}\rangle = \frac{B^2|0_e\rangle - AB|1_e\rangle + A^2|1\bar{1}_e\rangle}{\sqrt{A^4 + A^2B^2 + B^4}}, \quad (7)$$

$$|D_{\bar{1}1}^{(3)}\rangle = \frac{B^2|0_e\rangle - AB|\bar{1}_e\rangle + A^2|\bar{1}1_e\rangle}{\sqrt{A^4 + A^2B^2 + B^4}}, \quad (8)$$

$$|D_{\bar{1}\bar{1}}^{(3)}\rangle = \frac{B^2|0_e\rangle - AB|\bar{1}_e\rangle + A^2|\bar{1}\bar{1}_e\rangle}{\sqrt{A^4 + A^2B^2 + B^4}}, \quad (9)$$

where the superscript denotes the number of non-zero positional states contributing to the null state, and the subscript the numerical value of the final (leaf) state. Any state which is a superposition of the null states is also in the null space. So therefore the state which transfers a particle from the base to the equally weighted superposition of leaf nodes is the normalised sum of these states, i.e.

$$\frac{2B^2|0_e\rangle - AB(|1_e\rangle + |\bar{1}_e\rangle) + \frac{A^2}{2}(|11_e\rangle + |1\bar{1}_e\rangle + |\bar{1}1_e\rangle + |\bar{1}\bar{1}_e\rangle)}{\sqrt{A^4 + 2A^2B^2 + 4B^4}}. \quad (10)$$

Our notation allows us inductively explore both the total tree structure, and the vectors spanning the null space. So for example, consider adding another MRAP-type branch to an even node connected to site  $|0_e\rangle$  via a null state  $|D_i^{(j)}\rangle$ . The effect of adding these new links is to replace the state  $|D_i^{(j)}\rangle$  with two new states, which are

$$|D_{3i+1}^{(j+1)}\rangle = B|D_i^{(j)}\rangle + A^j|3i+1\rangle, \quad (11)$$

$$|D_{3i-1}^{(j+1)}\rangle = B|D_i^{(j)}\rangle + A^j|3i-1\rangle, \quad (12)$$

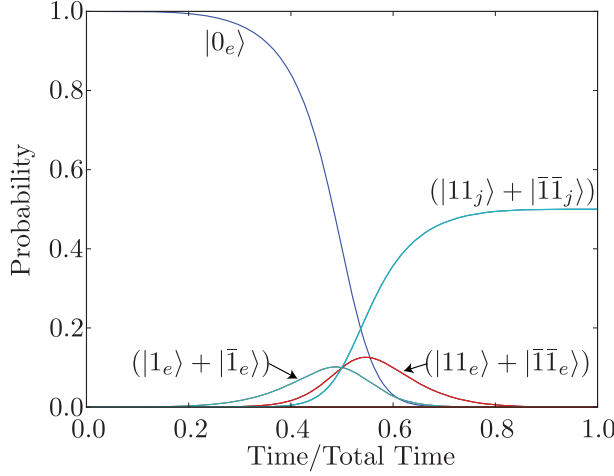
where the subscript on the  $D$  is represented in decimal form for simplicity. Although the tree structures are shown as if all leaf nodes are the same distance from the origin, in fact there is no requirement for this and the essential features of the transport protocol are unaffected by leaf nodes of varying distance to the origin.

With regard to interaction free measurement, the inductive method for generating the null states is particularly useful for understanding the properties of the network as a whole, but we can also use this method essentially *in reverse* to understand the effect of removing couplings from the network. Observe that for every null state, the population in all of the  $o$  nodes is zero. Trivially, if the TME connecting to a site with zero population on the left is also zero, then the population in any subsequent sites must be zero. In other words, a break in the chain immediately after an  $o$  site ensures that there cannot be any population in the remaining sites to the right of the break. Their contributions are removed from the null space. This insight immediately allows us to base an interaction free measurement protocol based on MRAP networks.

### 3. MRAP for imaging the quantum minefield

Here we turn to the task of how to use our protocol on a parallel IFM of a quantum minefield. This is a situation where there are a number of sites  $n$ , and a number of quantum bombs  $m < n$ , where  $m$  may be unknown. Our task is to determine the locations of the bombs without setting them off. This task may be accomplished by the network shown in Figure 2, where the minefield is located between the sites labelled  $i$  and  $j$ . Because breaks in the coupling for the tree remove states from contributing to the null space, and because the population in the site immediately before the broken chain is zero, the adiabaticity of the transport protocol forces every photon to avoid the broken link. This satisfies all of the requirements of an IFM. To more explicitly show how MRAP can be used for imaging objects, Figure 2 shows a typical configuration where this can be achieved. An excitation, such as a photon, starting from the root of the tree,  $|0_e\rangle$ , is transported via adiabatic passage to the leaves of the tree. An object, placed just before the leaf nodes, blocks the TME on the final  $o - e$  link (or not) revealing its presence or absence. This happens despite the fact that the photon is never found in a location adjacent to the bomb.

The observation that the null space of the MRAP tree is spanned by all of the null vectors that connect the base to the leaves immediately suggests a parallel IFM scheme. By altering the symmetry of a pathway, we can remove it from the null space, *without affecting the other null vectors*. Consider the tree depicted in Figure 2. In this arrangement, the MRAP tree is terminated by three-site CTAP pathways, which preserve the overall symmetry of the null space. However by removing the TME between the final two sites, the symmetry of the pathway is destroyed, and the vector connecting the leaf to the base of the tree is removed from the null space. We term the line between the final two sites as the imaging plane, and the object in this case



**Figure 3.** Adiabatic passage showing the evolution of the wave-function for the tree shown in Figure 2, as a function of the fractional time through the protocol, with two obscured imaging nodes ( $|1\bar{1}_j\rangle$  and  $|\bar{1}1_j\rangle$ ). The initial population is all in the state  $|0_e\rangle$  and smoothly evolves to the superposition  $(|11_j\rangle + |\bar{1}\bar{1}_j\rangle)/\sqrt{2}$ , with transient evolution in the states  $|1_e\rangle$ ,  $|\bar{1}_e\rangle$ ,  $|11_e\rangle$  and  $|\bar{1}\bar{1}_e\rangle$ .

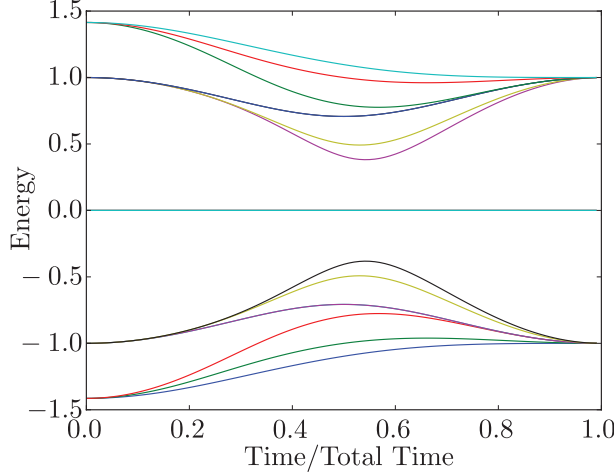
is assumed to occlude some subset of the paths. A particle adiabatically evolving through the network will be unable to explore the occluded pathways, and neither will it be able to occupy the site directly before the object. Hence the particle performs an IFM of the image plane in parallel, with the fidelity set by the adiabaticity of the overall protocol.

In the arrangement shown in Figure 2, the population of all odd states (eg.  $|0_o\rangle$  and  $|1_o\rangle$ ), in addition to the states  $|1\bar{1}_e\rangle$  and  $|\bar{1}1_e\rangle$  is (in the adiabatic limit) always zero. This follows from the fact that that neighbours of leaf nodes always have zero amplitude. Therefore, any excitation in the system has no probability of actually interacting with the object being imaged (or even undergoing adiabatic passage down a branch of the tree in which the an object is located). In this example, the excitation undergoes adiabatic passage from state  $|0\rangle$  to states  $|11_j\rangle$  and  $|\bar{1}\bar{1}_j\rangle$  where it can be safely detected. Similarly for any combination of objects obscuring the imaging nodes, the excitation proceeds directly to the imaging nodes which are not occluded, and never undergoes adiabatic passage down the branches of the tree which lead to an object.

Returning to the initial quantum bomb analogy, we can now imagine the parallel version - a quantum minefield placed in the imaging plane. The sensing particles will adiabatically explore the minefield, and will be unable to interact with sites with bombs (as they are removed from the null space). Measurements of the particles at the leaf nodes will definitively mark sites without bombs, and eventually the pattern of the bombs will be discovered to arbitrarily high accuracy, without the loss of *any* particles.

A typical evolution is shown in Figure 3. Here we show the results of evolution for the case depicted in Figure 2, i.e. with two obscured imaging sites ( $|1\bar{1}_j\rangle$  and  $|\bar{1}1_j\rangle$ ). If we write the state as  $|\psi\rangle$ , then the evolution is represented by  $|\langle i|\psi\rangle|^2$  for all sites  $|i\rangle$ . In this case adiabatic passage takes the excitation from the initial state  $|0_e\rangle$ , to





**Figure 4.** Energy level diagram for a two-level tree, with no object obscuring the imaging plane. The minimum energy gap occurs approximately halfway through the protocol, in accordance with expectations from other adiabatic passage protocols (CTAP, STIRAP and MRAP). Robustness of the protocol is guaranteed provided the rate of evolution is slow compared with this minimum energy gap.

the superposition  $(|11_j\rangle + |\bar{1}\bar{1}_j\rangle)/\sqrt{2}$ . In the adiabatic limit, all of the  $o$  and  $j$  sites are unpopulated, as are  $|\bar{1}\bar{1}_e\rangle$ ,  $|1\bar{1}_j\rangle$ ,  $|\bar{1}\bar{1}_e\rangle$ , and  $|\bar{1}\bar{1}_j\rangle$ , as expected by the IFM. Transient population is observed in intermediate states, as expected for the alternating protocol. The first maximum corresponds to the superposition (at time  $t \approx 0.49$ )  $|1_e\rangle + |\bar{1}_e\rangle$ , whilst the second maximum (at time  $t \approx 0.55$ ) to the superposition  $|11_e\rangle + |\bar{1}\bar{1}_e\rangle$ .

To ensure adiabatic evolution, a critical consideration is the energy gap between the ground ( $E = 0$ ) state and the first excited state. A typical energy level diagram for a two-level tree, with no object obscuring the imaging plane, is shown in Figure 4.

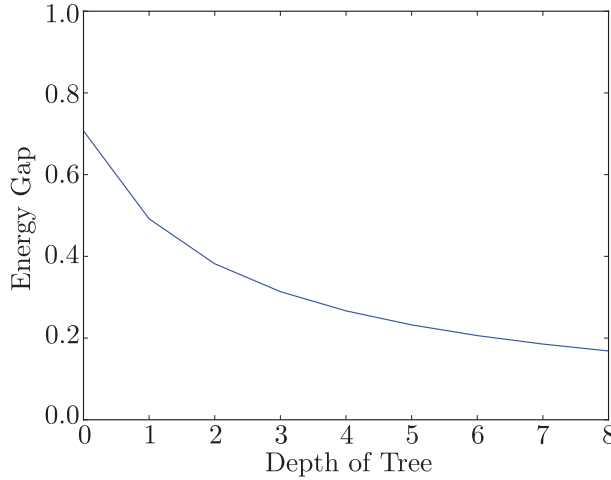
Initially, when  $A = 0$ ,  $B = 1$  there are five distinct, but degenerate energy levels. These are at  $E = 0$ , which has been discussed in detail in this paper, at  $E = \pm 1$  which are contributions from symmetric and anti-symmetric superpositions the imaging plane, and at  $E = \pm\sqrt{2}$  corresponding to symmetric and anti-symmetric superpositions across different levels of the tree.

As evolution proceeds, the minimum energy gap between the  $E = 0$  state and the excited states narrows. According to the adiabaticity criteria, for any two eigenstates  $|\psi\rangle$  and  $|\phi\rangle$ , adiabatic evolution is assured when

$$\frac{|\langle\psi|\dot{H}|\phi\rangle|}{(E_{|\psi\rangle} - E_{|\phi\rangle})^2} \ll 1. \quad (13)$$

For this reason, the energy gap is of crucial importance for maintaining the adiabaticity of the operation. Fortunately, for any reasonable level of tree, it is possible to determine the size of this gap, and show that it does not grow too small. Figure 5 shows a numerical calculation of the size of the minimum energy gap for up to a depth eight, or 256 imaging nodes.

This example may be extended to much larger trees, of much larger depth is a straightforward way. Additional nodes may be added in a tree-like structure to provide many more leaf nodes, and therefore many more locations for interaction free imaging.



**Figure 5.** Minimum energy gap between the  $E = 0$  state, and the first excited state for different sized trees, for the case that  $A_{\max} = B_{\max} = 1$ . Note the monotonic decrease in the energy gap with increasing tree depth, which implies that evolution through more complicated trees must proceed commensurately more slowly than for shorter depth trees.

If objects are placed in the imaging plane, then it is possible (after several iterations of the MRAP procedure) to determine the position of these objects to arbitrary accuracy. It should be noted that if objects can be placed at any level of the tree, it is only possible to determine which branches of the tree have been obscured by the objects, but not necessarily to determine their exact positions. For example, in our scheme one cannot distinguish between two bombs placed immediately before sites  $|11_j\rangle$  and  $|1\bar{1}_j\rangle$  and one bomb placed immediately before site  $|1_o\rangle$ . Care should also be taken to ensure that not *all* paths to imaging nodes are obscured. If this is the case, then when  $A \neq 0$ ,  $B \neq 0$  there is no longer a valid  $E = 0$  state, and it is possible to observe beating in the system.

#### 4. Collision-free routing

In this section we point out that the MRAP scheme as discussed offers another surprising result arising from the fact that a *local* change in the Hamiltonian produces a *global* alteration of the null states. This feature gives rise to the possibility of collision-free routing, which we describe below.

Imagine a distribution network where particles (possibly containing information, or halves of Bell pairs) need to be distributed from a starting node, to multiple recipients. Examples of protocols that could take advantage of such a network are quantum cryptographic networks where a base station wants to share random numbers for use as quantum keys with many users. So for concreteness let us assume that we are employing the MRAP tree to distribute qubits, and that there is no coupling between the qubit degree of freedom and the spatial degree of freedom. Returning to Figure 2 imagine that Alice is at site  $|0\rangle$ , and wants to distribute qubits to Bobs at the leaf nodes of the MRAP tree. Alice doesn't care which qubit goes to which Bob, but she does need to know the time stamp of arrival of the qubits (so that appropriate

correlations can be made during public basis comparison). Let us further assume that the Bobs need a certain amount of time to process the arrival of a particle (detector dead time), or that for other reasons (for example they have a full buffer of qubits) they do not wish to receive qubits. However, they do not wish to communicate with Alice or the Bobs when they want to receive particles.

In a classical setting with conventional routing, Alice would need to decide to which Bob she would send a particle. To avoid the dead time problem, there are many solutions which involve some scheduling of the distribution of qubits, however it seems that any such system will either enforce an effective clock rate, and possibly entail the ‘collision’ of qubits in the network, for example if two qubits are sent to the same receiver (Bob) during the dead time of the detection network. Remarkably, the MRAP approach provides an elegant solution to this problem.

For the IFM protocol discussed above, the breaking of a connection led to an alteration of the symmetry of the null space, thereby removing certain states from the null space. Adiabaticity of evolution then prevented particles from exploring the removed states. However, another way to remove states from the null space is simply to apply a small energy shift to the state. For example, if one of the Bobs, say at site  $|11\rangle$  in Figure 2 shifts the energy of their site, they will immediately remove their site from the null space, without affecting the rest of the null space. This result is interesting. It means that a local change in the Hamiltonian, affects the entire null space. However this change is not observable by the other Bobs or Alice. The net result is that to have a probability of receiving particles, the Bobs should ensure that their receiving site has zero energy. But if at any time they wish to cease receiving qubits, then they shift their energy. This could be because of detector dead time, or simply because they do not require qubits. Each Bob will receive particles randomly, collecting a fraction of the distributed particles sent by Alice equal to the rate of particles transmitted divided by the number of Bobs receiving particles. Finally, Alice need not know who is on the network, she only needs to continue transmitting at the rate available to her.

This surprising routing solution is interesting, and would seem to be ideally applied in an optical setting, again taking advantage of the structures similar to the CTAP waveguides networks demonstrated by Longhi and co-workers [9, 10].

## 5. Conclusion

We have explored the extension of the MRAP (Multiple Recipient Adiabatic Passage) protocol to explore adiabatic passage through tree-like structures. This MRAP tree affords a new method to realise interaction free measurement (IFM). The original quantum bomb problem was non-deterministic, and could only sense a single bomb. Our approach allows for deterministic parallel IFM arising from the adiabaticity of the protocol, and the perturbation to the symmetry of the null space introduced by the objects being imaged. Due to the adiabaticity of the protocol, this approach should be robust with respect to perturbations in the distribution network.

We have also shown that with a minor variation to the protocol, it can be used to effect a novel distribution network, where collision-free routing can be achieved. In particular where source distributes particles, but does not need to specify any of the routing. We are not aware of any classical protocol that can achieve these outcomes.

One issue with the scheme is that the MRAP protocol requires spatial coherence of the particle exploring the network. For this reason, a photonic implementation

would seem to be the only practical system to realise this network, although it is clear from the quantum mechanics that in principle, any quantum system could exploit these effects providing that the spatial decoherence rate is sufficiently long.

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